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Accelerating a car from rest: friction, power and forces

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Abstract

The directions of frictional forces for bodies in motion are conceptually challenging. Students may be able to provide a correct solution using only calculus without drawing free-body diagrams. This can make their misconceptions go unnoticed and put them at risk to become further reinforced. Here, we discuss first-year bachelor students' responses to multiple-choice questions and an open-ended question regarding friction when they come fresh out of high school. We further look into student solutions submitted to a national competition in physics for high-school students involving a problem concerning the acceleration of an electric rear-wheel drive car. Finding that most students had avoided drawing figures, we discuss to what extent teachers' grading practices contribute to students' development of problem-solving habits.

Keywords: acceleration, friction, free-body diagram, power, graphs, grading, pseudowork

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1. Introduction

'What is the minimum time required for a rear-wheel drive car with mass $M = 1545$ kg and maximum engine power of $P = 89$ kW to accelerate from rest to $100\,\mathrm{km\,h^{-1}}$ if the friction coefficient between the wheels and road is 0.8?' A typical plug-and-chug problem?

This situation was given to high-school students as the last problem of a national qualification test for the International Physics Olympiad in 2023. The problem text also stated that air resistance and other losses could be neglected. It is a problem that serves well to high-light students' conceptions about friction, work, and power, and on what level they approach a problem. It also led to discussions about how to grade different solutions in a fair and pedagogical manner.

Grading the solutions, common misconceptions concerning friction forces on accelerating cars were, unsurprisingly, high-lighted. As discussed in section 2, the friction forces acting on the rear driving wheels on an accelerating car are necessarily in the direction of motion. Many participants instead treated friction as a force opposing the motion of the car or drew a free-body diagram with the forces opposing the motion. This misconception is frequently encountered among first-year university students and has been noted by many teachers before us (see e.g., [1, 2]). We here briefly discuss our own findings on this topic, and connect to how the concept of mechanical work is elusive when static friction is involved.

As the problem statement looks like a typical textbook problem, most participants also approached it this way, i.e., working out time and distance using standard relations such as $v = at$ and $s = at^2/2$, once they had calculated $a \leqslant 0.4g$. As discussed in section 3, they did this without noting that this acceleration cannot be maintained for higher velocities, where the acceleration is limited by the engine power, i.e., $a \leqslant P/Mv$.

This paper provides a closer analysis of the solutions presented by the 70 participants who had the largest total number of points, and presents our reflections after grading the problem. In particular we focus on the conceptions of friction, and what resources students use when trying to solve the problem: Do they draw free-body diagrams, and use graphic representations, e.g., of the time-dependence of velocity, acceleration or power?

We finally discuss how we, as graders, value different parts of the presentation of the solution and what signals this sends to the students. By considering solutions from this select group of above-average students we are able to obtain valuable insights into what qualities in solutions they are used to seeing required and rewarded.

2. Conceptual friction challenges

Two of us have repeatedly been surprised and fascinated by the overwhelming majority of first-year university physics students who are confused about situations where the friction forces are in the direction of motion of a car. In these cases friction forces are opposing the rotation of the wheel, resulting in a forward force on the car.

Figure 1 shows a simple free-body diagram for a rear-wheel drive car accelerating on a horizontal surface, ignoring the friction on the front tyres. When drawing this type of free-body diagram, the vast majority of students manage to draw the normal forces $\boldsymbol{N}_\mathrm{r}$ and $\boldsymbol{N}_\mathrm{f}$ on the rear and front wheels, respectively. Most do not, however, draw them to scale compared to the magnitude of the force of gravity Mg. As Arons [3] noted 'Teachers are well aware that most students, when asked to draw force diagrams ('free-body diagrams') for interacting objects, sketch figures in which the numbers and directions of arrows are essentially random'. In the case of an accelerating car, the direction of the frictional force $\boldsymbol{F}_\mathrm{Fr}$ poses the greatest challenge.

2.1. Statements about friction—true or false?

What do students 'know' or assume about friction? For several years, two of us have posed the following multiple choice question to beginning first year university students: Which of the following statements about friction are true or false?

(i) A friction force always leads to energy losses.
(ii) The friction force is always in a direction opposite to the direction of motion.

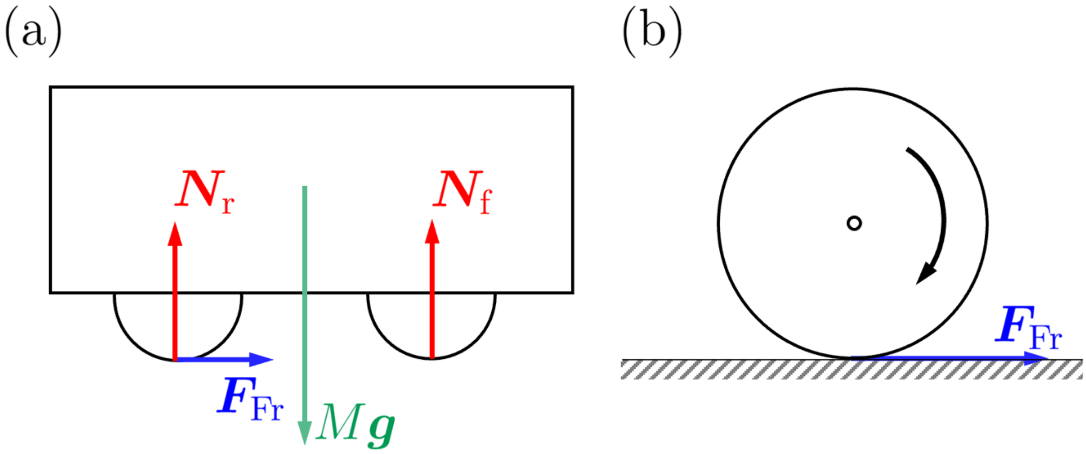

Figure 1. External forces acting on an accelerating car with rear-wheel drive (a) and on the rear wheel (b) as drawn by a few of the students. The largest difficulty for many students is that the friction force $\boldsymbol{F}_{\mathrm{Fr}}$ is in the direction of motion of the car. The energy required for the acceleration is provided by the engine transmitting a torque to the axles of the driving wheels (panel (b)), where the forward friction force exerts a (smaller) torque in the opposite direction. See also the discussion in section 2.4.

(iii) The friction force is always in the direction of motion.
(iv) The friction force is always parallel to the surfaces in contact.
(v) The friction force is always orthogonal to the surfaces in contact.

Of these, only (iv) is true. The majority of students claim that statement (i) is correct, although it does not hold for static friction. Also the second option (ii) is assumed to be correct by most students, although it does not hold for cars moving uphill or accelerating.

Figure 2. To probe student conceptions of forces, this picture was handed out, asking the students to draw all forces acting on a car driving slowly uphill, with constant speed.

2.2. *Driving uphill*

A question that requires an understanding of friction forces and Newton's first law is 'Which direction is the friction force on a car driving slowly, and with constant speed, uphill?' (figure 2). An overwhelming majority of first-year university physics students draw a downhill friction force, resulting in a free-body diagram where the forces do not sum to zero, but would lead to a large downward acceleration.

Chances are that the textbooks encountered by students—whether at high school or university—have 'solved' the conceptual challenge by avoiding it. One exception is found in [4] which includes a worked example of a 4-wheel drive car speeding up, and also asks a conceptual question whether sliding and static friction can accelerate an object and whether they can be used to increase the speed of an object. Another exception is the book by Chabay and Sherwood [5] who introduce the concept of a 'point particle system' where all forces that influence the centre-of-mass motion (i.e. translation) are included—but not rotational energy, nor internal energy—in their chapter about multi-particle systems. Also, Mazur [6] points out that static friction forces can accelerate a system without doing any work and includes an analysis of the force situation on an accelerating cyclist.

That this misconceptions about friction is widespread is to some extent further confirmed by a ChatGPT response (December 2022) to the question. It claimed that 'The friction force on a car driving slowly uphill would be opposite to the direction of motion. This means that the friction force would act in a direction that is downhill, or in the opposite direction of the uphill slope. This force is necessary to oppose the force of gravity and keep the car moving at a slow, steady pace up the hill.'. The claim was repeated when ChatGPT was asked to try again. ChatGPT is trained on a large corpus of text and, indeed, states on its opening page, https://chat.openai.com/chat, that it 'may occasionally generate incorrect information' (the inner workings of ChatGPT is presented in some detail in https://writings.stephenwolfram.com/2023/02/what-is-chatgpt-doing-and-why-does-it-work/).

2.3. Multiple-choice question about driving uphill

We also constructed a multiple-choice question: 'Which image in figure 3 gives the best representation of the forces acting on a car driving slowly uphill?' It was administered as a Mentimeter (mentimeter.com) question to a group of first-year physics students, at the end of their introductory course, but before their first university mechanics course.

The alternatives were based on a question from their previous lecture, where they were given a paper depicting the car driving uphill (figure 2), and asked to draw all forces acting on the car. They were allowed—and encouraged—to discuss with each other. After 15 min we collected their papers. Thus, all students had been exposed to the question and had discussed it among their peers prior to the multiple choice test.

Of the 23 students who answered the question in figure 3 during the following lecture, 7 chose the correct response D, whereas the others chose one of the responses C and E involving an 'engine force'. It is likely that fewer students would have got the right answer if they had not started thinking about it and discussed it during the previous lesson. However, we were pleased to note that several weeks later, a couple of weeks into their mechanics course, nearly all gave the correct response.

2.4. Friction, pseudowork and point-particle systems

How can the friction force increase the kinetic energy of the car? Sherwood has discussed this situation in a 1983 paper, noting that 'In teaching mechanics, we should more clearly distinguish between an integral of Newton's second law and the energy equation' [7]. For a system of particles the acceleration $\boldsymbol{a}_{\mathrm{CM}}$ of the centre-of-mass is given by the sum of all external forces,

$$\sum \boldsymbol{F}_{\mathrm{external}} = M\boldsymbol{a}_{\mathrm{CM}}. \tag{1}$$

The centre-of-mass equation (1) shows how the forward friction forces, acting on the rear wheels, change the centre-of-mass velocity. However, the friction forces do no work, since the point of application of these forces has no displacement, unless the wheels slip. Still the kinetic energy of the car increases during the acceleration, according to

$$\sum \boldsymbol{F}_{\mathrm{external}} \cdot \Delta \boldsymbol{s} = \Delta \left(M \frac{\boldsymbol{v}_{\mathrm{CM}}^2}{2} \right). \tag{2}$$

The left-hand side of (2) is *not* the work done on the car, and the right-hand side of (2) is not the change in the total energy of the car, but only of the kinetic energy of the centre-of-mass.

The change in total energy of the car includes several other terms, and may be written (neglecting air resistance) as

$$Q_{\mathrm{net}} = \Delta \left(M \frac{v_{\mathrm{CM}}^2}{2} \right) + \Delta E_{\mathrm{k,internal}} + \Delta E_{\mathrm{thermal}} + \Delta E_{\mathrm{battery}}. \tag{3}$$

The left hand side, Q_{net} 'is the net heat transfer into the car from the surroundings, consisting mainly of (negative) heat transfer from the hot engine to the air and from the hot tires to the cooler pavement'; $\Delta E_{\mathrm{k,internal}}$ 'represents the increased energy of motion of the internal parts of the car, including the engine and the wheels'; $\Delta E_{\mathrm{thermal}}$

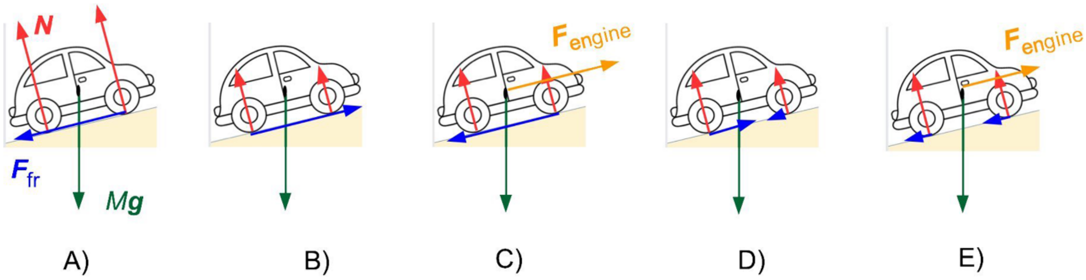

Figure 3. A multiple-choice question, based on the student responses to the question in figure 2. The alternatives C and E, involving an 'engine force' and friction forces opposing the motion, were found to be the most prevalent choices.

is associated with the change in temperature of the engine and the battery (friction, Ohmic heating, and irreversible aspects of battery discharge) and $\Delta E_{\text{battery}}$ is 'the (negative) change in chemical energy which pays for all the other terms in the equation' [7].

The engine provides a torque to the wheels, causing them to turn and exert a backward force on the road, which then, according to Newton's third law, pushes forward on the wheel, as indicated in figure 1(b).

Students often include an 'engine force' to make the car move uphill or speed up. However, the *force* exerted by the engine acts only on other internal parts of the car. Hence, this force is not a part of $\boldsymbol{F}_{\text{external}}$ in (1).

Sherwood [7], following Penchina [8], introduced the term pseudo-work for the left-hand side of (2), which gives the change in translational kinetic energy of the centre-of-mass. In a 2017 blog post, https://brucesherwood.net/?p=134 he tells about the struggle to publish that paper, and the response '... but that's not how we teach the subject'. In later work, Chabay and Sherwood [5, 9] instead work with the concept of a 'point-particle system'.

3. Solution to the competition problem

We now turn to the solution of the problem stated in the introduction. A first observation is that the friction force pushing the car is $F_{\text{Fr}} \leqslant \mu M/2 = 0.4Mg$, giving an acceleration of $a_0 = F_{\text{Fr}}/m \leqslant 0.4g \approx 3.9\,\text{m s}^{-2}$. If this acceleration could be maintained, the final speed, $v_{\text{f}} = 100\,\text{km h}^{-1} \approx 27.8\,\text{m s}^{-1}$, would be reached after $t = v_{\text{f}}/a_0 \approx 7.1\,\text{s}$ and after a distance $s = a_0 t^2/2 \approx 98\,\text{m}$. Figure 4 shows how velocity, acceleration, power and distance would vary if the acceleration would have been limited only by friction.

However, this problem is more difficult than the first impression may lead students to believe: The power required for an acceleration a depends on the velocity as

$$P = \frac{\text{d}}{\text{d}t}\left(\frac{Mv^2}{2}\right) = Mav, \tag{4}$$

which changes with time as the car accelerates. We can also use the relation $P/M = av$, which enables calculations with smaller numerical values. An acceleration $a_0 = 0.4g$ can thus only be maintained as long as the power required does not exceed the maximum engine power $P_{\text{max}} = 89\,\text{kW}$. This maximum power is reached for the velocity $v_{\text{b}} = P_{\text{max}}/(Ma_0) \approx 14.7\,\text{m s}^{-1}$, which happens after $t_b = v_{\text{b}}/a_0 \approx 3.73\,\text{s}$ and a distance $s_{\text{b}} = v_{\text{b}}t_{\text{b}}/2 = a_0 t_{\text{b}}^2/2 \approx 27.38\,\text{m}$.

3.1. *Power-limited acceleration*

Another unrealistic estimate of the time required to reach the final velocity $v_{\text{f}} = 100\,\text{km h}^{-1}$ is obtained by writing down the expression $E_{\text{k}} = Mv_{\text{f}}^2/2$ for the kinetic energy, and then calculating the time required for the engine to provide this kinetic energy. This gives $t = Mv_{\text{f}}^2/2P \approx 6.7\,\text{s}$.

This time, based only on power and energy, is obviously too short, since the acceleration in the beginning of the motion is much larger than the friction can provide. The distance for this first non-realistic part of the motion is also shorter than it would be for a maximum initial acceleration of $0.4g$.

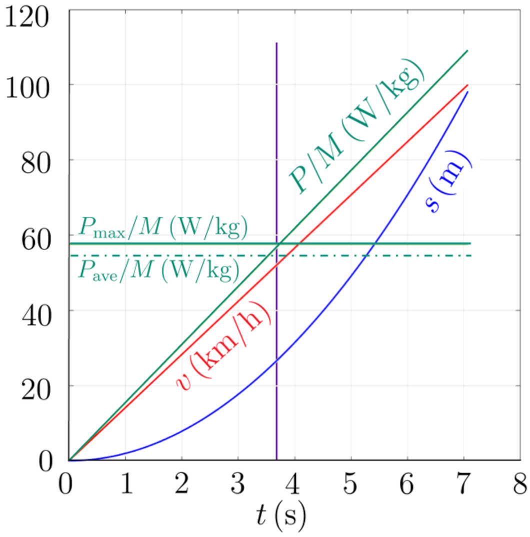

Figure 4. Velocity, distance and power for an acceleration limited only by friction, i.e. $a = 0.4g$. The horizontal solid line marks the maximum power given in the problem. The dotted line marks the average power until the car has reached $v = 100\,\mathrm{km\,h^{-1}}$. The vertical purple line marks the break point, where the critical speed is reached and power of the engine can no longer sustain an acceleration of $0.4g$.

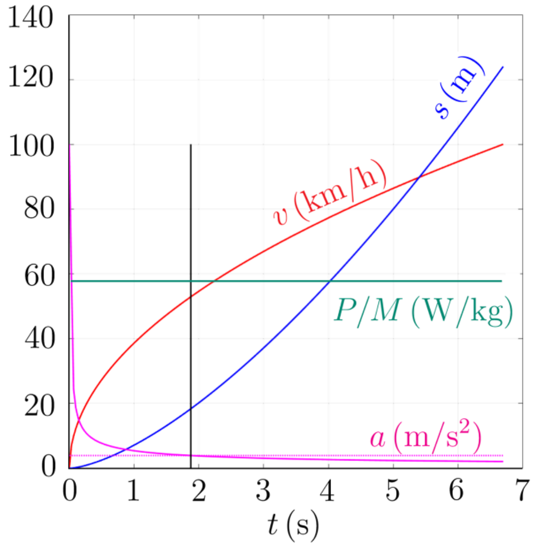

Figure 5. Velocity, distance, acceleration and power for an acceleration limited only by the power, i.e. $a = P/Mv$. The horizontal dashed line marks the maximum acceleration possible for the friction stated in the problem. The vertical black line marks the break point, where the friction is finally sufficiently large to make use of the maximum engine power without slipping.

Figure 5 shows how velocity, distance and acceleration would vary if the acceleration were limited only by the engine power. The maximum power cannot be used for velocities below the break point $v_b \approx 14.7\,\mathrm{m\,s^{-1}} \approx 52.9\,\mathrm{km\,h^{-1}}$. Note in particular that the acceleration from rest would be extremely large: standing up in a bus, you may sometimes have experienced very jerky starts. Physics teaching often misses out on opportunities to ask student relate idealized situations to their everyday experiences.

3.2. From friction-limited to power-limited acceleration

After an initial acceleration of $0.4g$ the power reaches it maximum value, and the acceleration drops. We then assume the power to be constant, $P = P_{\max}$, until the final velocity v_f is reached. The kinetic energy added during the acceleration from v_b to v_f is given by

$$\Delta E_k = \frac{M}{2}\left(v_f^2 - v_b^2\right) \approx 429\,\mathrm{kJ}. \tag{5}$$

This energy can be reached in $t_2 = \Delta E_k/P_{\max} \approx 4.83\,\mathrm{s}$, giving a minimum total time $t_{\mathrm{tot}} = t_b + t_2 \approx 3.73\,\mathrm{s} + 4.83\,\mathrm{s} \approx 8.6\,\mathrm{s}$. We can also express the kinetic energy as E_k/M which has the values $v_b^2/2 \approx 108\,\mathrm{J\,kg^{-1}}$ at the break point and $v_f^2/2 \approx 386\,\mathrm{J\,kg^{-1}}$. This yields $\Delta E_k/M \approx 278\,\mathrm{J\,kg^{-1}}$.

The second part, to work out the distance travelled as the car accelerates with constant power, is more challenging.

Using an expression for the velocity a time t after the break point, based on the kinetic energy gives

$$v(t) = \sqrt{v_b^2 + \frac{2P_{\max}t}{M}}. \tag{6}$$

Using this expression in the integral $s(t) = \int_0^t v(t')\mathrm{d}t'$ and using $s_2 = s(t_2)$ gives

$$\begin{aligned} s_2 &= \int_0^{t_2} \sqrt{v_b^2 + \frac{2P_{\max}t'}{M}}\mathrm{d}t' \\ &= \frac{M}{3P_{\max}}\left[\left(v_b^2 + \frac{2P_{\max}t}{M}\right)^{3/2}\right]_0^{t_2}. \end{aligned} \tag{7}$$

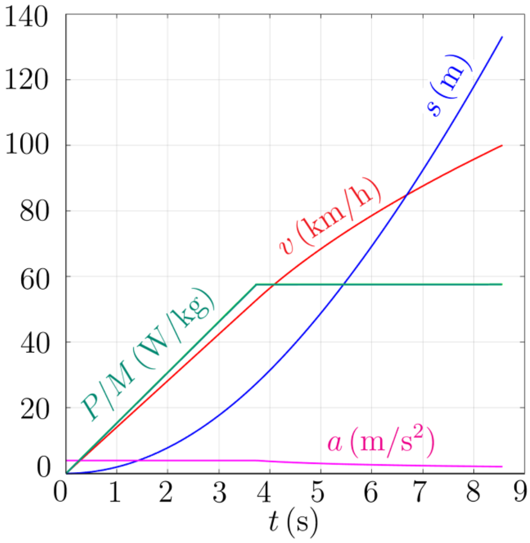

Figure 6. The variation of velocity, acceleration, power and distance for the maximum acceleration of the car. The motion consists of two stages. During the first stage, $t < t_b \approx 3.73\,\mathrm{s}$, the acceleration is friction-limited and remains constant. During the second stage, $t > t_b$, the acceleration a is limited by the maximum available engine power and a decreases with increasing speed.

With numerical values, we get $P_{max}/M = 57.6\,\mathrm{m^2\,s^{-3}}$ and find $s_2 \approx 106\,\mathrm{m}$. The minimum total distance is thus $s = s_1 + s_2 \approx 133\,\mathrm{m}$.

Figure 6 shows the time-dependence of velocity, acceleration, power and distance for the maximum acceleration possible.

3.3. Alternative solutions

The most original solution we found among the student solutions pointed out that driving over a precipice would give an acceleration of g, independent of friction and engine power. With large groups of students, there will now and then be an individual who thinks far outside the box, and provides an unexpected answer to the question—well aware that it is not the intended solution.

There were also more serious alternative solutions, using the average velocity (or acceleration) during the second part of the motion to estimate the distance.

From the velocity graph in figure 6, we can see that the average velocity $v_{ave} \approx 21.2\,\mathrm{m\ s^{-1}}$ would give only a slight underestimate, $v_{ave}t \approx 103\,\mathrm{m}$ of the distance for the power-limited part, and a total distance 130 m, only 3 m less than the result from the integral in (7).

The average acceleration during the second part might be calculated as $a_{ave} = (v_f - v_b)/t_2 \approx 2.7\,\mathrm{m\ s^{-2}}$, with the distance obtained as $s_2 \approx v_b t_2 + a_{ave} t_2^2/2 \approx 103\,\mathrm{m}$. This is again only a couple of metres shorter than the exact solution.

One of the student solutions made use of the relation

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}v}{\mathrm{d}s}\frac{\mathrm{d}s}{\mathrm{d}t} = v\frac{\mathrm{d}v}{\mathrm{d}s}, \tag{8}$$

which was then rewritten as $\mathrm{d}s = (v/a)\mathrm{d}v$. Inserting $a = P/Mv$ gives $\mathrm{d}s = (P/M)(v^2/a)\mathrm{d}v$. Integrating over the later part of the motion then gives

$$s_2 = \frac{M}{P}\int_{v_b}^{v_f} v^2 \mathrm{d}v = \frac{M}{P}\left[\frac{v^3}{3}\right]_{v_b}^{v_f} \approx 106\,\mathrm{m}. \tag{9}$$

4. Results

A total of 436 student solutions had been submitted from 75 high-schools, and 366 of them included attempts to solve this last problem.

The solutions from the 70 participants who got the highest total number of points were selected for analysis as part of a revision to check for consistency in grading the day after the joint grading event (two of these students had not attempted the final problem). The analysis focused in particular on whether the students had drawn a free-body diagram and any diagram to illustrate the time dependence, as well as their handling of the two different regimes relating to friction-limited or power-limited acceleration.

4.1. Diagrams as part of the solution

The general instructions for the competition included an instruction to draw figures, although that instruction was not repeated explicitly for this problem. However, the solutions sent to the schools after the competition and also posted online included no illustrations for any of the problems, which might signal to students that figures are not necessary.

Among the 68 solutions we analysed for the final problem, only 17 included diagrams of forces acting on the car. Out of these, only 11 showed the friction force acting in the direction of the motion of the car, similar to figure 1(a). Some of these solutions included a discussion of the motion of the wheel and how the friction force prevented the wheel from spinning, thereby exerting a forward force on the car (cf figure 1(b)). The remaining six solutions revealed the common misconception of friction forces acting backwards on the car, even as the speed increases. This view was hinted also in five solution sheets without figures. These solutions then included an additional forward force from the engine.

4.2. Friction-limited acceleration

The maximum acceleration $0.4g$ possible for a two-wheel-drive car with the friction coefficient 0.8 is obtained in a couple of lines by using algebra. However, most of the 31 students who calculated the numerical value $3.93\,\mathrm{m\,s^{-2}}$ arrived at this result after a page or more of calculations involving numerical values. Less common attempts involved the use of the value of $\mu = 0.8$ to obtain a slope of an inclined plane, or as a measure of engine efficiency.

Of the 68 solutions analysed, 16 assumed uniform acceleration at $0.4g$ to calculate the time, 7.1 s, and distance, 98 m to reach $100\,\mathrm{km\,h^{-1}}$. In 5 of these solutions, the students checked that the *average* power was less than the maximum power of the car.

Students using a solution based only on the frictional force were awarded 1 point, also for cases were the students checked that the engine power was sufficient to provide the final kinetic energy, $E_{k,f} = Mv_f^2/2 \approx 0.596\,\mathrm{MJ}$ in about 6.70 s. Students who had calculated the time and/or velocity at the break point received 2 p. A diagram indicating how velocity and/or energy varied with time earned students an additional 1 p of the maximum 5 p for the problem.

4.3. Only power-limited acceleration

Among the solutions we considered, we found 13 students who had performed the calculation for constant power, as outlined in section 3.1, 7 of them without making any remark about the need to consider the two different regimes. Only one of

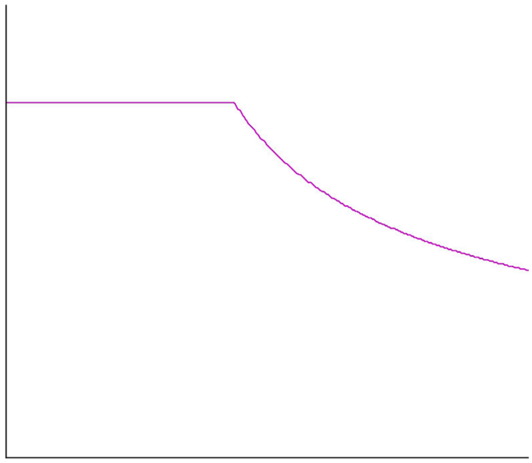

Figure 7. Simple sketch of the time dependence of acceleration, as drawn by a few of the students.

the students who used this approach drew a graph of the time dependence of acceleration for constant power, as included in the graph in figure 5, and noted that there has to be a break point, since constant power could only be applied to the later part of the motion.

4.4. Graphs to clarify the solution

Only 6 students had included graphs showing the time dependence of acceleration, velocity or power (cf figure 6), typically just a simple sketch of the acceleration, as in figure 7. Graphs exhibiting the break point are helpful for the grading teacher, but probably also for the students, as support during the solution process: a couple of students made use of the graph as they reached the solution by using an average velocity or acceleration for the part where acceleration was limited by the engine power. Two of the students had used a numerical solution to solve the integral, and three students managed to perform the analytical integration to obtain the correct result.

5. Discussion

Dealing with friction can be challenging, not least in situations involving internal energy conversions, as discussed in section 2. End-of-chapter or exam problems can often be solved without worrying about these conceptual problems. Unless students are required to draw free-body diagrams, their conceptual problems may remain unnoticed.

The competition problem in focus in this paper also required consideration of two distinct parts, where the acceleration was initially limited by friction. However, since the power required is proportional also to the speed, the acceleration will be limited by power after a critical speed is reached, as discussed in section 3.

Drawing figures is always a good approach to problem solving. For example Young and Freedman [10] (p31), in the setting-up part of their box on 'Solving physics problems' recommend that 'If appropriate, draw a sketch of the situation described in the problem. (Graph paper and ruler will help you make clear useful sketches.)'

As we grade student solutions, we may have an ambition to make students learn—the hard way if necessary—that figures and units are important, not only for the grader, but also for the student to assist the thought process and to check solutions. Writing down a sentence or two between equations is another good habit that helps both student and grader to follow the line of thought. Do we as teachers reward good habits with the strategies we use to grade student solutions? What signals do our grading and suggested solutions send?

Henderson [11] interviewed faculty about how they would solve a mechanics problem and how they would grade student solutions. He found that teachers were torn between placing the burden of proof on the student (to show that they understand what they are doing) and on the teacher (to demonstrate that a student does not know, in order to deduct a point), as well as a reluctance to subtract points from a brief solution reaching the correct result or conclusion.

A risk for the student elaborating the solution is thus that they may write down a comment that is incorrect, resulting in lost points. A risk for the teacher of not insisting on figures, is that misconceptions may go unnoticed. For the case of the accelerating car, it is reasonable to assume that a large fraction of the 51 solutions without figures would have added an 'engine force' and/or a friction force opposing the motion, if a free-body diagram had been required.

The cover page for the test stated that figures should be drawn, but the majority of the grading group for this problem thought it did not apply since it was not stated explicitly in the problem text. This view seems to have been shared by at least 51 of the 68 students whose solutions we analysed—and probably also by many of their teachers.

What instructions do we give students—and when do we train them to read instructions?

6. Conclusion

Cars accelerating or driving uphill are familiar occurrences in everyday life, but less common in physics textbooks' discussions of forces, where the analysis often focuses on 'rigid bodies'. The situation in the competition problem in focus of this paper should invite a discussion about free-body diagrams. It requires a conscious separation between forces acting on or within a system, as well as a realization that the friction forces that prevent the wheels from sliding are in the direction of motion of the car. The problem also invites a discussion about the difference between translational energy and total kinetic energy. That the power required for uniform acceleration varies is another observation rarely emphasized in textbooks.

We hope that the problems discussed in this article can invite many challenging and rewarding small-group or classroom discussions, and that the analysis presented here can prepare teachers for using the problems with their own students. Drawing figures, such as figures 1 and 6 (or 7) should be part of those discussions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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